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STATUS AND PROSPECTS OF HEAT-POWER ENGINEERING

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An attempt to estimate the technical level of power plants firing fossil fuel is made. Tendencies of development and updating processes used at these plants are analyzed together with the existing problems and ways for their solution. The condition of Russian power plants is considered against the background of the state of the world heat-power engineering. Attention is devoted to long-term problems like reduction of CO_2 emissions into the atmosphere and prediction of the structure of generating plants until 2050.

Keywords: power plant, fuel, coal, natural gas, pressure, temperature, steam, combined-cycle plant, efficiency.

In the last 75 years mankind has satisfied its demand for power primarily by utilizing fossil fuels: first coal, then oil, and then natural gas, in growing amounts.

Historically, both domestic and world heat power industry developed in several interconnected directions, namely,

— enlargement (increase in the unit power) of power units and plants;

— elevation of the efficiency of transformation of fuel heat into electric energy due to improvement of thermodynamic cycles and circuit design of equipment and plants;

— use of combined production of electric energy and heat.

This development was aimed at meeting the growing demand of the economy, reducing the costs, and preserving the environment.

The state of today's coal-fired power plants has formed as a result of this development about forty years ago.

Large coal-fired power plants are now equipped with steam power units with an output of up to 1300 MW (about 10 coal-fired generating units with two-shaft steam turbines have served for 20 – 30 years in the USA). They operate at subcritical (17 MPa) and supercritical (24 MPa) pressure, temperature of superheated steam of up to 540°C, and one intermediate reheating at 540 – 565°C. The efficiency of such power units designed and commissioned 20 – 30 years ago amounts to 40% at supercritical pressure.

Power boilers are commonly designed for spray firing of pulverized coal and dry or, more rarely, tap ash removal. The combustion efficiency of such boiler is high due to the use of special burners and burning methods with limited oxidation of nitrogen contained in the air and in the fuel and formation of toxic nitrogen oxides (NO_x).

In the case where environmental regulations cannot be met with the help of process measures (acting on the burning process), chemical selective reduction of nitrogen is resorted to, which includes selective catalytic (SCR) and noncatalytic (SNCR) reduction processes. The catalytic method ensures reduction of a higher fraction of NO_x and uses 2 – 3 times less reducing agent (primarily ammonia) than the noncatalytic method, but the unit cost of realization of the catalytic reduction process is an order of magnitude higher.

Ash particles formed in combustion from the mineral part of the coal and removed from the boiler conduit with flue gases are arrested with an efficiency of 99.5% or more by precipitators and bag filters.

The latest technologies can ensure binding of 95 – 99% SO_2 contained in the flue gases of boilers firing sulfur-bear-

Fig. 1. Niederaussem thermal power plant (Germany). A generating unit with an output of 1 million kW operating on brown coal.

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ing fuel. The most widely used processes employ washing of the gases by solutions of natural limestone or lime in a scrubber, which yields commercial mineral white as a by-product.

In addition to pulverized coal, crushed coal can be fired in a circulating fluidized bed (CFB). Long residence of coal particles in the furnace part in a highly turbulent fluidized layer with active heat and mass transfer ensures full burning of carbon even from a low-thermal-value and ash-rich fuel at a process temperature of 850 – 900°C. At this temperature slagging and superheating of the tubes can be avoided; the limestone added into the fluidized bed binds the sulfur contained in the coal, and thermal nitrogen oxides do not form. These advantages explain the wide range of application of boilers with CFB, first at plants with a moderate capacity (up to 300 tons/h) and then at more powerful plants (up to 1000 tons/h in late designs).

Data on the unit cost of large coal-firing thermal power plants and its distribution with respect to the kinds of equipment and systems used are presented in Table 1 [1]. The data are given for developing countries with high enough engineering and production potential and can be helpful for comparative estimates and discussion of problems of further advancement of heat-power technologies.

In Russia, coal with low quality (at coal consumption of about 122 million tons a year the total amount of dead matter in the fuel exceeds 55 million tons, including 31.5 million tons rock and over 24 million tons moisture; the ash content of about 30% of the entire consumed coal exceeds 40%, the combustion value of 12.5% coal is below 12.5 MJ/kg or 3000 kcal/kg) and unstable characteristics is frequently fired at condensing plants with generating units with an output of 150, 200, 300, 500, and 800 MW (the boiler capacity is 450 – 2650 tons/h) and at thermal power plants with boilers with a capacity of up to 1000 tons/h. At an output of less than 250 MW the pressure of the live steam is 14 MPa; at an output of 250 – 300 MW and higher supercritical pressure of 24 MPa is employed. Condensing plants with an output of 150 MW and higher and dual-purpose plants with an output of 180 and 250 MW have a reheat stage. The temperature of the reheat steam is commonly 540/540°C, but at many dual-purpose plants it attains 555°C.

Steam turbines of Russian producers are quite reliable in operation. Fifteen to twenty years ago the in-commission rates of 200 – 1200-MW steam turbines amounted to 97 – 99% for many years at an operating time of 6 – 7 thousand h/year, interrepair periods of 4 – 5 years, and time to failure of up to 10,000 h.

Some engineering solutions developed by domestic turbine makers were unique. For example,

— the regulating stage of the 50-MW LMZ turbine consisting of rotor blades welded into packs by electron beam welding with the use of design damping;

— last-stage blades of the low-pressure cylinder 1200 mm long produced from a titanium alloy (the annular area of the

TABLE 1. Specific Cost of Thermal Power Plants (in 1997 US$ per 1 kW)

Equipment and systems	Type of TPP and process								
	Pulverized-coal-fired TPP with subcritical steam pressure	Pulverized-coal-fired TPP with supercritical steam pressure	Perspective coal-fired TPP	CCP with super-critical boiler	Natural-gas-fired CCP	CCP with coal gasification	Pulverizedcoal-fired TPP with ultra-supercritical steam pressure	CCP with external coal firing	Natural-gas-fired fuel cell
Coal preparation	28	25	23	35	–	32	23	25	–
Cleaning of synthesis gas	–	–	–	–	–	69	–	–	–
Steam-water conduit	146	179	179	162	45	85	297	140	40
Control equipment and automatics	75	75	75	99	47	84	75	52	61
Boiler/high-temperature heat exchanger	203	217	256	357	–	–	325	453	–
Waste-heat boiler	–	–	–	39	99	114	–	107	102
Gas turbine unit	–	–	–	63	117	120	–	117	60
Steam turbine	129	130	131	169	63	71	178	74	62
Civil construction	192	189	181	136	54	108	170	143	123
Fuel cell	–	–	–	–	–	–	–	–	1000
Cleaning of flue gases	96	85	78	41	–	–	73	261	–
Designing	58	63	73	123	45	104	91	160	169
Gasifying unit	–	–	–	–	–	512	–	–	–
Electrical equipment	89	89	89	115	49	93	89	54	184
Budgeting	80	80	91	107	65	117	128	133	178
Total	1096	1132	1176	1466	584	1509	1447	1614	1979

Note. For coal-fired TPP with subcritical steam parameters the steam pressure is below 20.0 MPa and the steam temperature is below 540°C; for TPP with supercritical steam pressure the parameters are 26.0 MPa and 580°C; for TPP with ultra-supercritical steam pressure the parameters are 37.5 MPa and 700°C; for the perspective TPP the steam parameters are 30.0 MPa and 610°C.

stage is 11.3 m^2, the peripheral velocity is 658 m/sec), which have been serving successfully since 1983;

— solid-forged low-pressure turbine rotors with a mass of 80 tons without central bore used in high-speed LMZ turbines (3000 rpm) with an output of 1 million kW for nuclear power plants.

Russian turbine plants producing 300 and 800 MW, which have no deaerator and are equipped with mixing low-pressure preheaters that perform feed water deaeration sufficient for neutral oxygen water chemistry, are operating successfully. Some such turbines have long worked with non-flammable oil in the lubrication system. Russian turbines are highly unified in design and production.

Operating coal-fired boilers of domestic TPP are characterized by mechanical underfiring of about 0.5% for brown coal, 1 – 1.5% for black coal, and up to 4% for low-reaction lean coals and anthracite fines that are fired with ash tapping at an efficiency of 88 – 92%. Furnace methods for lowering NO_x formation have been developed for modes of firing brown and black coals, as well as SNCR processes and a very effective ammonia-sulfate process for sulfur removal, in which the sorbent is ammonia and the by-product (commercial ammonium sulfate) is a good mineral fertilizer.

Several experimental coal-fired boilers, i.e., a small-size boiler with a capacity of 500 tons/h equipped with a swirl furnace for firing Kansko-Achinskii coals and slag drip developed by the Central Boiler and Turbine Institute, a boiler with a capacity of 420 tons/h with low-temperature swirl burning of crushed (with pieces up to 25 mm in size) brown coal developed by the Leningrad Polytechnic Institute, boilers with combined flare-layer firing, and a boiler with a capacity of 420 tons/h for firing brown coal in a bubble fluidized bed developed by the Barnaul Plant together with the Central Boiler and Turbine Institute and the All-Russia Thermal Engineering institute, have been constructed for testing novel furnaces and firing processes. The difficulties arising in testing of these new boilers have not been eliminated fully for various engineering and economical reasons. A powerful (800 tons/h) boiler with a circular furnace constructed later is being tested at the present time.

Russia does not have boilers with CFB, though commercial projects of such boilers with different capacity have been created over 10 years ago. The designs are promising for firing low-grade fuel, which requires sulfur and nitrogen catching. Such conditions exist at 40 Russian TPP with over 250 boilers 140 of which have a steam rate of 200 – 240 tons/h and 56 require urgent reconstruction.

The Russian power industry widely uses combined production of power and heat and centralized integrated heating from power plants.

Russia is a cold country. It spends about 400 million tons coal equivalent for the production of heat, which amounts to over 40% of the total consumption of all kinds of fuel in the country. Heat is produced by thermal power plants (TPP) (241 general-purpose plants and 244 industrial plants) and boiler plants of various capacities. Over 70% of heat is produced in systems with integrated heating of which about 45% is taken from TPP due to steam from turbine extractions.

Combined production of power and heat for integrated heating was used even before World War II. After 1950 maximum attention was devoted to raising the efficiency of TPP. The live steam parameters were increased, i.e., the pressure to 13 MPa and the temperature to 565°C. The first steam turbine with an output of 50 MW was produced in 1957 and had industrial (1.3 MPa) and heating (0.25 MPa) steam extractions. A 100-MW steam turbine with two-stage heating of delivery water at a pressure of 0.05 – 0.2 and 0.06 – 0.25 MPa in the extractions was created. It had a special bundle for heating delivery water in the condenser. In 1970 a 250-MW steam turbine with supercritical pressure of live steam (24 MPa, 540°C) and reheat at up to 540°C was commissioned. The last two turbines were designed to cover the heating demand. The capacity of the turbines supplying steam for industrial purposes was raised in parallel. A 135-MW turbine of the kind was commissioned in 1973.

At the present time the total power of the thermal power plants of the "United Power System of Russia" Company amounts to 63 million kW (48% of the total power produced by the holding); the power of the thermal power plants of other owners adds about 15 million kW. The "UPS of Russia" owns TPP with high (14 MPa) and supercritical (24 MPa) steam pressure with total output of 52 million kW. These TPP work with the number of hours of use of electric power estimated at 4 – 4.5 thousand hours a year, that of heat power estimated at 3 – 4 thousand hours a year, and an available fuel heat factor of 60 – 65%. Combined production of electric power and heat gives annual saving of no less than 20 million tons coal equivalent.

In the last 10 – 15 years great success has been achieved in the field of turbine aerodynamics, and design and methods of production of power equipment. Comprehensive advancement of the equipment and optimum design of power units and plants has raised their efficiency to 42% at subcritical steam parameters and to 43 – 43.5% at traditional supercritical steam parameters [2] at strict observation of requirements on nature conservation (see Tables 1 and 2 [3]). The use of these achievements in domestic practice has made it possible to raise the efficiency of the designed 200-MW brown-coal power unit No. 3 of the Kharanoyarsk state regional power plant (SRPP) to be commissioned in 2007 to 41% and higher at steam parameters of 14 MPa and 560/560°C and to decrease the consumption of heat by 10% relative to the standard K-200 power generating units.

High-temperature steels with 9 – 12% chromium were developed in parallel. Their use for the production of massive unheated parts (steam conduits, rotors and casings of turbines, fitment) made it possible to raise the steam parameters to 29 MPa and 600/620°C and the efficiency of coal-fired power units to 45 – 47% (Table 1). Such coal-fired power units with an output of 380 – 1050 MW (with a two-shaft turbine) successfully operate in Denmark and Ja-

pan [4, 5]. The best Japanese generating units operate with an efficiency of 45 – 46%. Danish generating units operating on colder circulation water at higher vacuum have 2 – 3% higher efficiency. FRG possesses brown-coal-fired generating units with an output of 1 million kW, steam parameters of up to 27 MPa and 580/600°C, and efficiency of up to 43% [6]; a "banner" coal-fired power unit with an output of 600 MW has been developed [7]. The appreciation of power plants with powerful (600 – 800 MW) generating units upon growth in the steam parameters and use of more expensive steels for the purpose is evaluated at 2.5% when the efficiency rises from 43 to 45% and at 5.5% when the efficiency rises to 47%. The appreciation pays its way at high cost of the coal (Fig. 2).

Domestic heat-power industry has developed progressively with growth in steam parameters. The USSR was one of the first countries widely using supercritical pressure at power plants. Its experience and successes have been acknowledged in the world. As early as in 1949 the TPP of the All-Russia Thermal Engineering Institute (VTI) launched a small boiler with steam parameters of 30 MPa and 600°C and later 650°C. Until the present, the boiler has served for over 200,000 h.

A pilot SKR-100 power unit with a boiler with a capacity of 720 tons/h and topping turbine with an output of 100 MW rated for steam parameters of 30 MPa/650°C has operated for over 30,000 h at the Kashira SRPP in the 1960s.

Modern developments achieved in cooperation with domestic producer plants have shown that it is possible to create a power unit with steam parameters of 30 MPa and 600/650°C at an output of 300 – 600 MW and efficiency of about 46% in Russia in the nearest future [8].

Earlier-designed power equipment with supercritical steam parameters was oriented toward the use of austenitic steels with high coefficients of linear expansion and low thermal conductivity. This caused complications in the operation of massive parts produced from these steels at power units inevitably serving in a cyclic mode.

The next generation of units operating at high pressures and temperatures (the piping of the last bundles of boiler superheaters, outlet headers, steam conduits, turbine casings

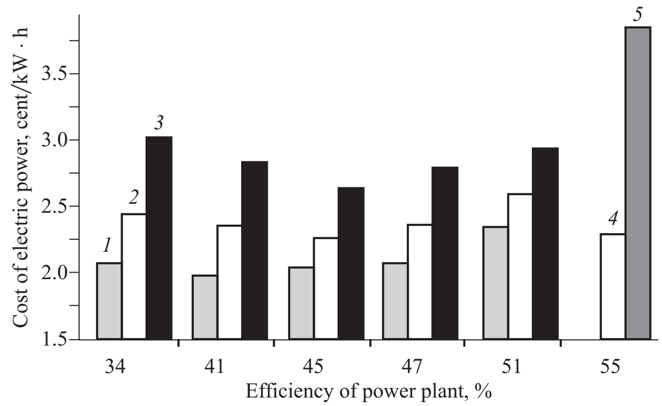

Fig. 2. Increase in the efficiency of pulverized-coal-fired power units. Coal cost: *1*, 0.4 $/MJ; *2*, 0.8 $/MJ (average value for the USA); *3*, 1.4 $/MJ (in the world market); gas cost: *4*, 2.6 $/MJ (average annual value for the USA in the last several years); *5*, 5.2 $/MJ (*4* – *5*, CCP operating on natural gas).

and rotors) will be produced from nickel alloys, which are actively tested in Europe, USA, and Japan. The use of such alloys will make it possible to raise the temperature of superheated steel to 750°C and later even to 870°C.

A joint effort of scientific organizations and companies of European countries is directed at developing a pulverized-coal-fired power unit with live steam parameters of 37.5 MPa and 700°C and double reheating to 720°C at a pressure of 12 and 2.35 MPa. At a pressure of 1.5 – 2.1 kPa in the condenser the efficiency of such a generating unit should exceed 50%, and further advancement might give 53 – 54% [5]. Novel compact layouts are studied for decreasing the use of the most expensive materials and reducing the specific cost of such generating units, which is now expected to be very high (Table 1).

Another promising direction in the development of coal-fired TPP is the use of combined-cycle technologies.

Today these technologies dominate at power plants operating on natural gas and are advancing dynamically.

The first power gas turbine unit (GTU) was commissioned in Russia in 1939. At the initial gas temperature of

TABLE 2. Parameters of Coal-Fired TPP Planned in the USA [3]

Parameter	Initial level	2010	2020
Removal of sulfur, %	98	99	>99
NO_x emission, g/MJ (mln^{-1})	65(110)	4.3(7.5)	4.3(7.5)
Emission of particles, g/MJ (mg/m^3)	4.3(12)	2.2(6)	0.9(2.5)
Removal of mercury, %	–	90	95
Use of by-products, %, %	30	50	<100
Efficiency, %:			
with respect to high heat value	40.0	45 – 40	50 – 60
with respect to low heat value	41.4	46.5 – 51.6	51.8 – 62
In-commission rate, %	>80	>85	≥90
Specific cost of TPP, $/kW			
Cost of electric energy, cent/(kW · h)	900 – 1300	900 – 1000	800 – 900

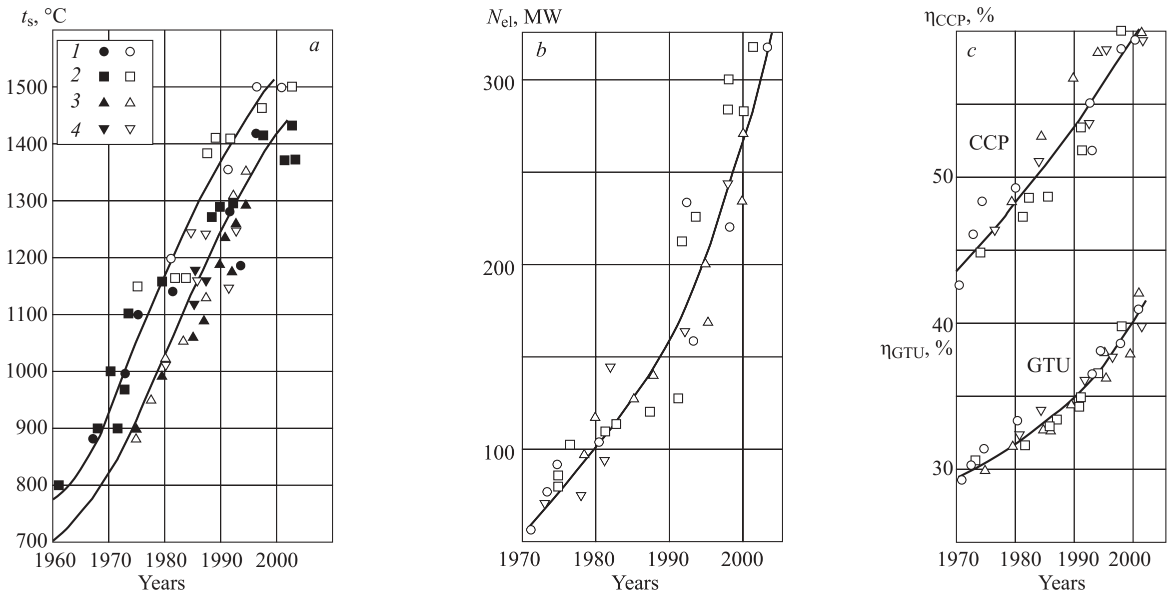

Fig. 3. Dynamics of growth in the parameters and characteristics of power GTU and CCP: *a*, gas temperature in power GTU [black symbols present the mean stagnation temperature at the entrance to the first-stage turbine rotor blades; white symbols present the mean temperature at the exit from combustion chamber (at the inlet to the nozzles of the first turbine stage)]; *b*, output of power GTU; *c*, efficiency of power GTU and CCP: *1*, GTU of the Mitsubishi Company; *2*, GTU of the General Electric Company; *3*, GTU of the Siemens Company; *4*, GTU of the Alstom Company.

550°C its output was 4 MW and the efficiency was 18%. After World War II gas turbine engines progressed intensely in the aircraft industry and somewhat later the achievements in this field were applied to the power industry. The dynamics of the process is reflected in Fig. 3.

Modern gas turbine plants have reached a high level of engineering perfection. Today they operate at an initial gas temperature of 1300 – 1400°C, degree of compression of 17 – 23, and efficiency of 38.5% in an autonomous mode. Multi-shaft gas turbine units created on the basis of aircraft engines with high degrees of pressure growth at a unit power of up to 40 – 55 MW have an efficiency exceeding 40%. The highest unit power of power GTU has reached 335 MW. As a rule, these are simple-cycle units operating at maximum gas temperature permissible for engineering and economical considerations, which is growing continuously. Their compressor and turbine are mounted on one shaft and rotate at an optimum speed that increases with decrease in the unit power. At an output of less than 100 MW it is transferred to the shaft of the electric generator through a reducer. The two-bearing rotor has no bearing in the zone of high-temperatures and pressures.

This zone is localized in a compact block of turbine machines with an annular or modular-annular combustion chamber built in between the latter. The number of parts operating in the zone is not great and the parts themselves are well-proven and intensely cooled with cycle air (quire recently commercially produced GTU have been equipped with new components, i.e., gas collectors of the combustion chamber and steam-cooled nozzle and rotor blades of one to two first turbine stages). These pasts are fabricated from complexly alloyed nickel-base (more rarely cobalt-base) alloys, preserve a high strength at 800 – 850°C, and withstand local temperature growth on the surface to 950 – 1000°C. Nozzle and rotor blades of complex shape with intricate systems of internal cooling are fabricated from these alloys by the method of precision casting sometimes (recently) with directed crystallization or can even be single-crystal.

GTU employ "low-toxicity" combustion of natural gas ensuring NO_x concentrations ≤20 – 50 mg/m^3 in the combustion products. This is a result of formation of a homogeneous gas-air mixture and compression of the mixture at a high excess air factor (α = 2 – 2.1) and uniform and comparatively low flare temperature (1500 – 1550°C). First successes have been achieved in the use of a similar technology for firing liquid petroleum fuel.

In modern high-capacity power GTU the waste gas temperature is 550 – 640°C. Their heat can be used for heat supply or for production and reheating of steam to 540 – 565°C, which then expands in the steam turbine. The efficiency of such GTU at the already functioning TPP amounts to 55 – 59%. Ways have been determined for raising this efficiency to 60 – 62%. This high efficiency is attained in binary CCP, where all of the fuel is burnt in the gas turbine. Such CCP have been built in the last 20 years, because their high efficiency is combined with a moderate specific cost (Table 1) and high reliability. The operational parameters of the GTU and CCP are no worse than those of conventional steam-power equipment of TPP.

In addition to large steam-power plants a considerable number of GTU with an output of 50 MW is used for regional (industrial and municipal) power supply often com-

bined with heat supply. Many power GTU of this class are produced by air-engine makers on the basis of available engines. It is natural that this affects the design of the GTU. They have several shafts, i.e., a gas generator (a former air-engine) with one, two, or three compressors that are rotated by their own turbines and form coaxial shafts and a combustion chamber. The gases outgoing from the low-pressure turbine of such a unit have a high temperature and considerable pressure and expand in the power turbine, the power of which is transferred to an electrical generator. The combustion chamber and the control system are also changed with respect to transport applications. The best of such GTU have steady service lives at high efficiency, mobility, and factory service.

The next step in the development of combined cycles for the heat power industry will be the creation of "hybrid" installations where GTU and CCP will be replenished with a fuel cell (Fig. 4) [9].

High-temperature fuel cells operating at 850°C (solid oxide ones) and 650°C (based on molten carbonates) can serve as power sources for a gas turbine or a steam-gas cycle. In the latter case we will have a tertiary system rather than a binary one. Results obtained for specific installations primarily in the USA show the possibility of efficiencies at a level of 70% for operation on natural gas with internal reforming for CO and H_2. A fuel cell can also be fed by synthesis gas or pure hydrogen obtained, for example, by coal gasification. In the programs developed the possibility of raising the power of hybrid installations to 300 MW and higher at an efficiency of up to 75% for the gas-fired mode and up to 60% for the coal-fired mode is considered. In the "breakthrough" project of zero emission coal-fired TPP [10] an efficiency of 70% is considered. The difficulties are connected with the high cost of fuel cells and the limited power of individual cells that are hard to combine within one unit. For this reason the first commercial power units with fuel cells are expected to have a small size (from 3 – 5 to 100 – 300 kW) and be used for individual generation of electric power and heat.

Unfortunately, gas-turbine and combined-cycle units are not yet used widely in the Russian industry. A considerable number of GTU with an output of 1.5 – 12 MW based on transport (aircraft and ship) engines operate at enterprises of the extractive industry in remote regions. The largest GTU producing 100 MW have been used since 1970 for load factoring in power systems and operate on liquid fuel.

The first domestic CCP rated for 200 MW (35-MW GTU, 165-MW steam turbine) and equipped with a high-pressure steam generator (HPSG) with a capacity of 450 tons/h was commissioned in 1973 at the Nevinnomyssk SRPP. The pressure in the furnace of the HPSG amounts to 6.5×10^5 Pa, and the gas temperature at the inlet to the turbine is 770°C. At present the CCP has served for 185,000 h.

In 1979 – 1980 two CCP rated for 250 MW were installed at the Moldavian SRPP. The exhaust gases of the CCP were fed to the furnace of a conventional boiler of a K-200 unit, where they were used for oxidizing the boiler fuel oil.

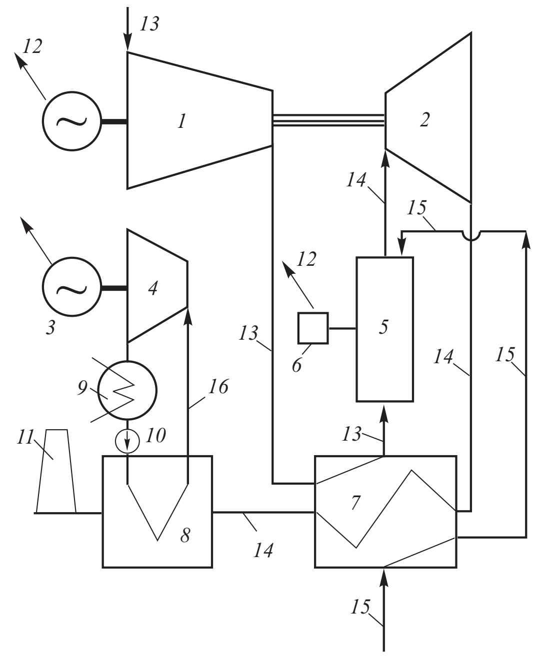

Fig. 4. Hybrid power plant: *1*, compressor; *2*, GTU turbine; *3*, electric generator; *4*, steam turbine; *5*, fuel cell battery; *6*, inverter; *7*, heat exchanger; *8*, waste-heat boiler; *9*, condenser; *10*, pump; *11*, smoke stack; *12*, power to network; *13*, air; *14*, products of fuel oxidation; *15*, cleaned natural gas; *16*, steam.

Both types of CCP have operated well, but their efficiency did not exceed that of oil-gas supercritical-pressure units due to the small fraction of the gas turbine power and low parameters of the GTU. The first advanced CCP (two GTU rated for 150 MW each and a steam turbine of the same capacity with an efficiency of 50% in the condenser mode) was commissioned at the North-West Cogeneration Plant of St. Petersburg in 2001. On November 1, 2004 the operating time of the CCP was 28,000 h at a mean load of 360 MW and an efficiency of 47.7% [the specific consumption of coal equivalent was 258 g/(kW · h)].

An original gas turbine plant with an output of 100 MW developed with allowance for the experience of transport gas turbine engineering is successfully operating at the Ivanovo SRPP. The design power is ensured at an efficiency of 35%.

At the same time, the Russian TPP consuming an enormous amount of natural gas require updating and changeover to operation in the combined-cycle mode.

Installation of a GTU — exhaust-heat-boiler unit (like that of the North-West TPP of St. Petersburg) at a thermal power plant and feed of the steam produced to T-100 or PT-80 turbines should raise the electric power by a factor of 2.3 – 3, the output in the heating mode by a factor of 2 – 2.5, and the efficiency in the condensing mode from 35 to 49%, and will make it possible to convert 45 – 47% of the fuel heat into electric energy at a full heat load instead of 30%.

At condensing power plants with generating units rated for 150, 200, and 300 MW it is possible to realize CCP with different types and numbers of powerful (110 – 250 MW)

gas turbines while preserving all or some of the steam power units. At an optimum engineering solution the efficiency of the power plant can be raised from 35 – 40 to 50 – 55% [11].

It is expedient to use low- and medium-power GTU for combined production of electric energy and heat in small and medium cities supplied from gas-firing boiler plants and at industrial enterprises.

It is natural that such updating will require much investment and solution of many difficult organizational and engineering problems, but its advantages are enormous (saving of 30% natural gas spent for production of electric energy!) and the effort is worth making.

In principle, the thermodynamic advantages of combined cycles demonstrated by CCP operating on natural gas can be used in operation on contaminated fuel, for example, coal.

Gasification of coal or black oil can give synthesis gas suitable for firing in GTU after cleaning. A gasification installation operates at underpressure and is integrated into a CCP, the cycle and layout of which remain the same as in the mode of firing natural gas. At a high (2 – 7 MPa) pressure the processes of gasification and cleaning of synthesis gasfrom ash and sulfur compounds is intensified, whereas the size and cost of the equipment required for the processes decrease. The heat and/or steam removed from the gasification unit are used in the cycle of the CCP, from which the steam, water, and sometimes air necessary for the gasification are extracted. The losses appearing in the gasification unit reduce the efficiency of the CCP, but it can be high enough [40 – 45% with respect to the initial coal at the experimental plants (Table 3)] at an appropriate design.

Methods of gasification in a bulk and fluidized layer and in a flow have been developed well and find application. Commercial processes for cleaning synthesis gasfrom sulfur require cooling of the gas to a temperature close to atmospheric (40°C), which is accompanied by additional losses in the pressure and operating capacity. This makes CCP with coal gasification quite intricate and expensive (Table 1).

In order to be used widely they should have an efficiency of 52 – 55% and a specific cost close (100 – 105%) to that of the competing coal-fired steam power units at emissions to the environment presented in Table 2.

Such parameters can be attained by further improvement of the efficiency of GTU and advancement of components and systems of CCP.

The losses in the operating capacity due to gasification can be reduced from 16 – 20 to 10 – 12%, and the consumption of electric energy for auxiliaries can be lowered by the following measures:

— lowering of the temperature of combustible gas at the outlet from the gasification unit to 900 – 1000°C;

— cleaning of the combustible gas from sulfur compounds and particles and feeding it to the combustion chamber at an enhanced temperature (for example, 500 – 540°C at which the pipelines and accessories can be produced from inexpensive steels);

— use of air blasting instead of oxygen blasting;

— reduction of pressure and heat losses in the gas-air conduit of the gasification system and use of closed heat exchange loops.

Table 3 illustrates the quantitative proportions corresponding to this situation.

It is also expected that with the development of the technology and growth in the output and unit power the specific cost of CCP with coal gasification will decrease considerably.

In recent years CCP with gasification are treated as a power technology complex producing electric power, heat, or steam and hydrogen, which is obtained with the help of gasification of an excess amount of fuel and steam conversion of carbon monoxide contained in the synthesis gas by the reaction

$$H_2O + CO \rightarrow CO_2 + H_2.$$

This process has been realized at commercial CCP with gasification of black oil.

Over ten such CCP with an output of up to 500 MW have been operating in the world for 5 years. They are located near

TABLE 3. Heat Balance and Main Losses at CCP Operating on Natural Gas and Coal (all values are given in percent of the low heat value of the fuel taken as 100%)

Parameter	Natural-gas-fired CCP	CCP with gasification	
		existing	planned
GTU power	37	28 – 30	32 – 34
Steam turbine power	23.0	23.0	22.5
Gross efficiency	51 – 53	56 – 57	
Losses:			
with flue gases	17.0	12.0 – 13.5	14.0 – 15.0
in condenser	24	27 – 28	27
other	1	2 – 5	2
due to gas cleaning	–	5	3
Fuel heat transferred to steam	–	10 – 15	5
Consumption for auxiliaries	1.5	10.0	6.0
Net efficiency	58.5	45.5 – 48.0	52.5 – 53.5

large refineries, get fuel from the latter, and supply the latter with different kinds of energy.

In Russia CCP with gasification were developed actively in the 1980s. In 1987 – 1991 the All-Russia Thermal Engineering Institute and the Central Boiler and Turbine Institute in cooperation with design organizations performed a detailed study of several types of CCP with unit power (net power) 250 – 650 MW within the state program on "Ecologically Safe Power Industry." The three mentioned gasification processes were studied as applied to the most available coals, i.e., the brown coal of the Berezovskoe deposit, the black coal of the Kuznetskii basin, and anthracite fines, which differ considerably in composition and properties. The efficiencies obtained ranged from 39 to 45%.

On the whole, these projects matched the then world level. Today the research of CCP with gasification in Russia is limited.

Another type of coal-fired CCP is known and has been used for about 15 years [2]. In this type of plant the combustion chamber of the GTU is replaced by a high-pressure steam generator (HPSG), in which coal is fired in a fluidized bed under pressure (FBP) at a temperature of about 850°C at air excess in the boiler. Air is fed into the bed by a GTU compressor, and the combustion products expand in the turbine after cleaning from the fly ash. The heat emitted from the fluidized layer and the heat of the gases fired in the turbine is used in the steam cycle. The high pressure (about 1.5 MPa) in the bed intensifies all the processes and permits lowering of the sizes of the steam generator at full combustion of the coal and small concentrations of NO_x and SO_2 in the combustion products. Thermodynamically, such a system is less effective because a greater part of the fuel heat is fed directly to the steam cycle. However, the losses are also substantially lower than in that in the case of gasification. The actual final efficiency of such CCP is at a level of 41% at a plant output of 100 MW (15 MW GTU and 85 MW steam turbine) and subcritical steam parameters and at a level of 43.5% at an output of 365 MW (75 MW GTU and 290 MW steam turbine) and supercritical steam parameters.

The possibilities of the development of this type of CCP are connected with increasing the gas temperature at the inlet to the turbine. For this purpose the fuel in the layer should be fired at enhanced air excess, and an additional combustion chamber should be mounted between the HPSG and the turbine; a part of the coal (or the whole of the coal partially) should be gasified.

Recently, the development of thermal power plants is hindered by social discussions of the possibility of catastrophic global changes stimulated by growing emissions of carbon dioxide due to combustion of fossil fuel and by the policy of governments reflecting this anxiety. Without going into the validity of this anxiety, which is not shared by all specialists [12], we should mention that if these doubts prove justified, competitive TPP or power technology enterprises operating, for example, on coal but emitting inconsiderable amounts of CO_2 into the atmosphere can be created in several decades.

At the present time the goal can be reached by economically expedient measures like energy saving by consumers, raising of the efficiency of operating power units (replacement of old inefficient plants by updated and more efficient ones), and development of combined-cycle productions of electric energy and heat.

A principal solution consists in creating systems with removal of CO_2 from the layout of power plants and burying it underground or deep in oceans. Thermal power plants can be equipped with

— CCP with coal gasification, steam conversion of CO yielding hydrogen, and extraction of CO_2 from the synthesis gas;

— power units firing the fuel in a medium of oxygen and CO_2. In this case the combustion products consist of condensable water vapors and CO_2, a part of which circulates back into the furnace and the other part is removed from the loop to be buried;

— traditional power units with washing of flue gases for binding CO_2 and its subsequent extraction.

CCP with gasification are expedient for new construction; in principle, washing of the flue gases can be organized at the operating steam or combined-cycle units.

These possibilities are widely studied in various countries for determining and optimizing the layout and the equipment. It is natural that they are connected with additional losses and use of additional equipment, which worsen the parameters of the TPP and increase the cost of electric energy. Figure 5, which reflects data of various studies including [13], which are based on considerable research but are not always consistent, shows that the specific cost of TPP can increase by 10 – 80%, the specific consumption of heat by 10 – 35%, and the cost of electric energy by 30 – 100%.

In parallel, specialists are searching for possibilities of advancement of methods for lowering the losses due to separation and burial of CO_2 and studying ways for perfecting the realized or technically clear methods and processes and novel, sometimes exotic, ideas such as membrane separation of gases (air, converted synthesis gas), new sorbents and solvents, oxidation of fuel with formation of solid stable products, and other approaches. It can be expected that successes in these studies and commercial realization of the technologies will lead to considerable growth in the efficiency of power plants with removal of CO_2.

In planning the construction of new TPP operating on fossil fuel and designing them, we should at least think of additionally equipping them with systems for removing and treating CO_2 and provide measures for integrating additional elements into the layout. This equally concerns steam power plants and CCP with coal gasification.

On the whole, recent estimates show competitiveness of production of electric power at TPP with binding, separation, and burial of CO_2. Figure 6 presents the cost and possible volumes of reduction of CO_2 emissions into the atmosphere

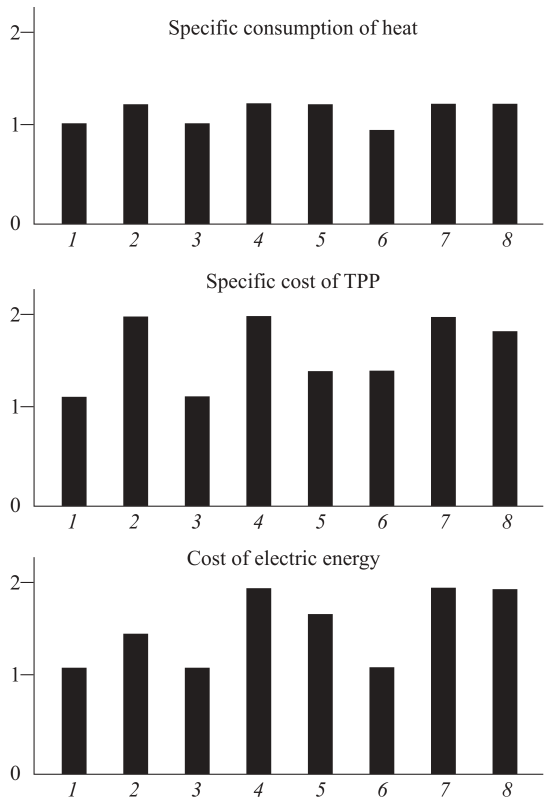

Fig. 5. Comparison of processes of CO_2 removal: *1*, *2*, natural-gas-firing CCP (η = 58%); *3* – *5*, units with supercritical steam pressure (η = 46%); *6* – *8*, CCP with gas circulation ($\eta \geq$ 46%); *1*, *3*, *6*, without removal of CO_2; *2*, with arresting CO_2; *4*, washing of flue gases from CO_2; *5*, *7*, coal firing in a mixture of O_2 and CO_2; *8*, separation of CO_2 after the shift reaction.

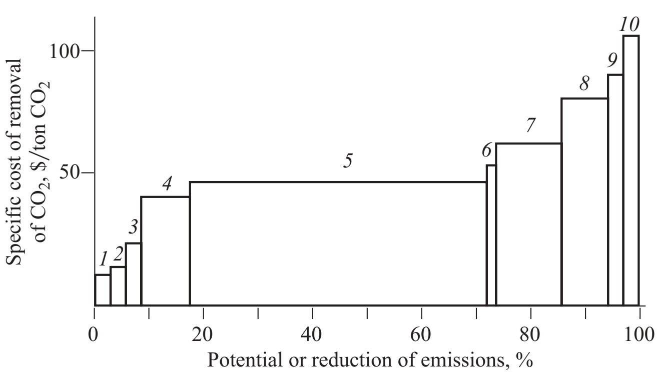

Fig. 6. Possible fraction and specific cost of reduction (prevention) of CO_2 emissions (according to the data of L. Stromberg, Vattenfall, Sweden): *1*, replacement of coal by gas; *2*, change in the grade of coal; *3*, replacement of fuel oil by gas; *4*, replacement of coal in remote future; *5*, withdrawal of CO_2 from combustion products; *6*, reforestation; *7*, use of biological fuel; *8*, hydropower plants; *9*, wind resources; *10*, solar energy.

by various methods. It can be seen that at a specific cost of 1 ton CO_2 equal to 45 dollars separation of CO_2 from combustion products can ensure over 50% of the required reduction

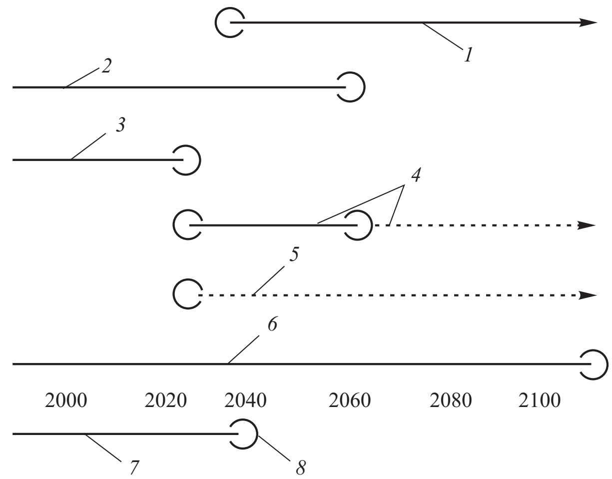

Fig. 7. Prediction of time boundaries of the use of various technologies of conversion of fossil fuel into electric energy: *1*, fuel cells operating primarily on gas; *2*, traditional coal-fired power plants; *3*, traditional fuel-oil power plants; *4*, CCP with gasification (scenario with high emissions); *5*, gas-fired CCP with removal and burial of CO_2 (scenario with low emissions); *6*, CCP operating on natural gas; *7*, gas-fired steam units; *8*, end of transition to CCP.

of CO_2 emissions. The use of biological fuel, wind and solar energy, and hydraulic resources is more expensive, and the potential of these measures for preventing CO_2 emissions is much lower. It should be taken into account that the earlier mentioned studies are aimed at reducing the cost of the separation of CO_2 to 20 – 25 \$/ton or even to lower figures. This should raise the attractiveness of the respective technologies and widen their application.

The brief review presented shows the stable position of thermal power plants in the field of production of electric power and heat, availability of engineering possibilities for improving the heat power technologies and equipment, and promise of substantial increase in their efficiency. Radical engineering solutions should provide power services to mankind and keep its habitat.

At attempt to predict the advancement of heat power engineering with time with allowance for engineering possibilities and economic expediency is made in [14]. The results are presented in Figs. 7 and 8. It can be seen from Fig. 7, for example, that fuel-oil steam turbine power plants will be used until 2025, and gas-fired plants will be used until 2035; the use of CCP with coal gasification will become substantial after 2025, and that of gas-fired fuel cells after 2035; gas-fired CCP will be used even after 2100; separation of CO_2 at them will be started after 2025; in CCP with coal gasification this will occur after 2055.

The possible scale of the changes is estimated in Fig. 8, where we present electric power production predictions (mean, minimum, and maximum values) with the use of various technologies in 2050. For example, it is assumed that coal-fired CCP with separation of CO_2 will pro-

duce 55 EJ (minimum 20, maximum 160) electricity (1 EJ = 278 × 10^9 = 278 billion kW · h).

Despite the uncertainty of such predictions they reflect the essence of long-term processes in the power industry and possible directions of development of the power technology.

Unfortunately, Russia does not participate appropriately in this process. Fifteen to twenty years ago the Russian power industry was at a very advanced level (except for GTU and automation systems). New processes and equipment were developed, which were not inferior to foreign counterparts. Powerful branch and academic institutes worked on the topic.

In the last 10 – 15 years the potential attained in power engineering and machine building has been exhausted to a great degree. Development of novel equipment has virtually stopped and new power plants were not constructed. Gas turbines (GTÉ-110) and process control systems (KVINT and Kosmotronik), which were a considerable step forward, were rare exceptions but did not eliminate the lag.

With allowance for physical wear and obsolence the Russian power industry demands renewal. However, the present economic conditions are not favorable for active investment in the industry. Given that such conditions are created, domestic research organizations will be able to design and produce advanced equipment for the power industry. Such production will be connected with high expenses and some risk for the owners of power plants until the requisite experience is accumulated. It is necessary to find a source for compensating the expenses and the risks, because it is clear that domestic production of power equipment is in the national interest.

Research should be performed with the aim of advancing the existing and developing new technologies of production of electric power and heat. In recent years the financial support of such studies has been miserable and their organization leaves much to be desired. As a result we are turning from a country developing new technologies into a country consuming them.

The engineering policy, organization of fundamental and applied studies in power engineering, and creation of new objects for demonstration of novel processes and equipment should become a purpose of the State. Budget investment has to be increased markedly and conditions should be created for attracting private capital to research in the power industry. The State should take an active part in determining the directions of scientific and engineering research and creation of equipment and share the inevitable risks. The latter is very important under the conditions of a market economy, when private companies working under competition and having little experience, tradition, and taste for innovations are ignoring science.

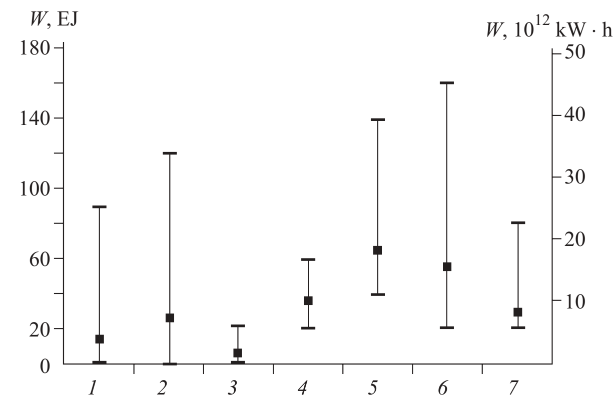

Fig. 8. Prediction electric power production *W* in 2050: *1*, coal; *2*, fuel cells on hydrocarbon fuel; *3*, solar cells; *4*, nuclear power plants; *5*, gas-fired CCP with removal of CO_2; *7*, conventional gas-fired CCP.

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